Flame-Vortex Interactions Imaged in Microgravity - To Assess the Theory of Flame Stretch

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Abstract. The goals of this research are to:

1. Assess the Theory of Flame Stretch by operating a unique flame-vortex experiment under microgravity conditions in the NASA Glenn 2.2 Second Drop Tower (drops to identify operating conditions have been completed);

2. Obtain high speed shadowgraph images (500-1000 frames/s) using the drop rig (images were obtained at one-g, and the NASA Kodak RO camera is being mounted on the drop rig);

3. Obtain shadowgraph and PIV images at 1-g while varying the effects of buoyancy by controlling the Froude number (completed);

4. Numerically model the inwardly-propagating spherical flame that is observed in the experiment using full chemistry and the RUN 1DL code (completed);

5. Send images of the flame shape to Dr. G. Patniak at NRL who is numerically simulating the entire flame-vortex interaction of the present experiment (data transfer completed); and

6. Assess the feasibility of obtaining PIV velocity field images in the drop rig, which would be useful (but not required) for our assessment of the Theory of Flame Stretch (PIV images were obtained at one-g using same low laser power that is available from fiber optic cable in drop tower).

The motivation for the work is to obtain novel measurement needed to develop a physically accurate model of turbulent combustion that can help in the control of engine pollutants. The unique experiment allows, for the first time, the detailed study of a negatively-curved (negatively stretched) flame, which is one of the five fundamental types of premixed flames. While there have been studies of flat flames, positively-curved (outwardly-propagating) cases and positively-strained (counterflow) cases, this is the first detailed study of a negatively-curved (inwardly-propagating) flame.

The first set of drops in the 2.2 Second Drop Tower showed that microgravity provides more favorable conditions for achieving inwardly-propagating flames (IPFs) than 1-g. A vortex interacts with a flame and creates a spherical pocket, which burns inwardly.. Shadowgraphs at 1000 frames/sec quantify the Markstein number and flame speed. A Low-Laser Power PIV System was developed and is being added to the drop package.

Numerical computations were required to explain why the Markstein numbers measured for the inwardly-propagating flames differ from those of outward propagating flames; this is an important research issue in the assessment of the Theory of Flame Stretch. The RUN-

1DL code (developed by Prof. B. Rogg) was run for IPF and OPFs with complex methane and propane chemistry. Results confirmed that Ma for the IPFs are larger than for OPFs as was observed experimentally. Physical reasons for these new findings about the Theory of Flame Stretch are being determined from the experiments and the computations.

Several journal papers have been published; the drop package is described in the AIAA Journal [1], while the one-g results appear in three other journal papers [2-4].

Experimental Apparatus and Results:

Figure 1 shows the University of Michigan Microgravity Flame-Vortex Drop Rig. A chamber is filled with a lean mixture (either propane-air or methane-air). Two electrodes ignite a flame kernel that becomes a flat flame. Pulsing a loudspeaker creates a laminar toroidal vortex ring that moves upward and interacts with the flame. For the proper conditions, the interaction creates a pocket of unburned reactants that is surrounded by an inward-propagating spherical flame. Figure 2 shows images of the spherical flame in the microgravity environment during drop tests. The third image on the left side of Fig. 2 shows that a spherical pocket has been formed. The bottom two images on the right side of Fig. 2 shows how a pocket is first forming and then how it burns out. The pocket is typically 5 mm in diameter initially. The propagation flame is dR/dt, where R is the radius of the pocket determined from shadowgraphs. The stretch rate is (2/R) dR/dt and also is determined from shadowgraphs. The Theory of Flame Stretch predicts that propagation speed S_L and the nondimensional stretch rate Ka) are related by :

$$S_L/S_{L,O} = (1 + \mathrm{Ma}\ \ \mathrm{Ka})^{-1} \qquad (1)$$

Ma is the Markstein number. Faeth [5] and Law [6] have determined Ma for outward-propagating flames, but our experiments [2] have shown that Ma of IPFs are 2-3 times larger than for OPFs, as seen in Fig. 3. Microgravity conditions on the drop rig provide a larger range of conditions for which spherical flames can be produced, so that values of Ma can be obtained using Eq. 1 for a wider range of fuel types and equivalence ratios than at one-g. Computations using RUN 1DL [7] were run in this study and they confirm our measurements; Fig. 4 shows that Ma is larger for an IPF than for an OPF. The physical reason for our findings is being determined from the experiments and the computations.

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2. Ibaretta, A. F., and Driscoll, J.F., "Measured Burning Velocities of Stretched Inwardly-Propagating Premixed Flames", Proc. of the Combustion Inst, Vol 28, 2000.
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4. Mueller, C., Driscoll, J. F., Reuss, D. and Drake, M., Comb. Flame:112, 342 (1998).
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7. Rogg, B. *Reduced Kinetics Mechanisms*, Peters, N. and Rogg, B., (Eds), Springer-Verlag, Berlin, 1993.

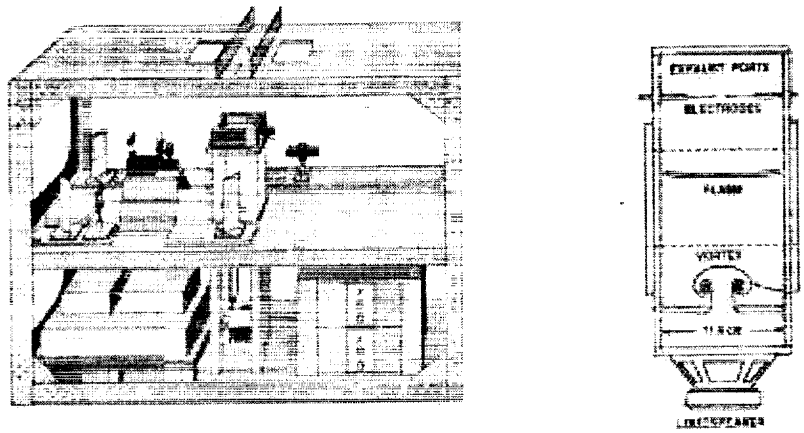

Figure 1. Schematics of the University of Michigan Premixed Flame-Vortex Interaction Drop Rig and the Combustion Chamber

Top Shelf: Pulsed Xenon ShadowgraphWhite Light Source, Shadowgraph optics, NASA Glenn Kodak RO High Speed Video Camera, Sony low-speed Video Camera. Bottom Shelf: Light source power supply, batteries, power distribution box, Tattletale computer, video optical cable transmitter, solenoids for flame-vortex experiment.

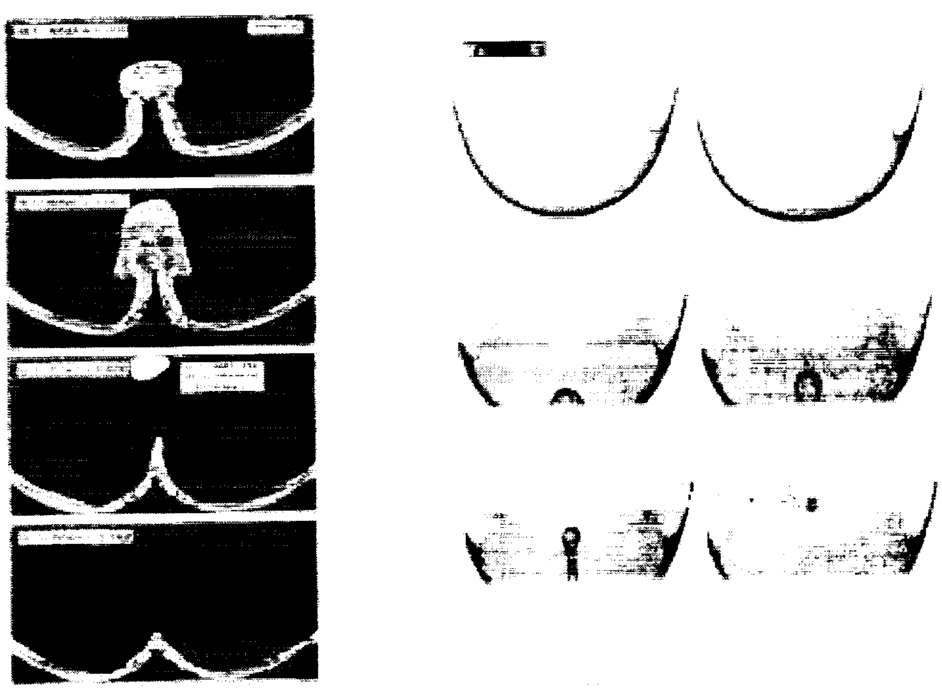

Figure 2. Video Images Obtained During Microgravity Drops - of a Vortex Creating a Pocket of Reactants Surrounded by an Inwardly-Propagating Spherical Flame

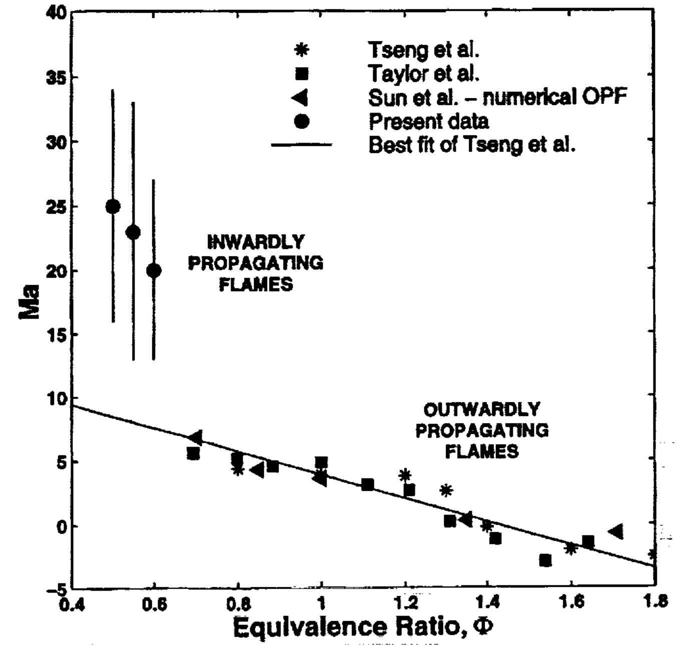

Figure 3.Measured Markstein Numbers of the Inward Propagating Flame in the Flame-Vortex Interaction Drop Rig at One-g [2]. Only a limited range of equivalence ratios create spherical flames at one-g; microgravity conditions provide a wider range of test conditions.

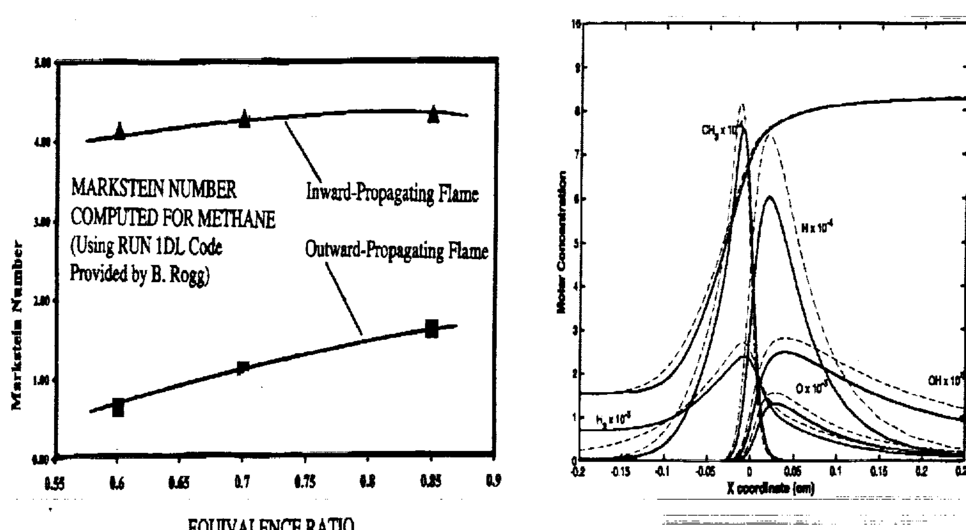

Figure 4. Computations Using Full Methane-Air Chemistry of the Inward-Propagating Flame Observed in the Experiment. RUN 1DL Code was used and conditions were set equal to our experimental operating conditions. Computations explain our significant experimental finding that Markstein number of inward-propagating flames is larger than that of outward-propagating flames.